Description of new shock-induced phases in the meteorites of Shergotty, Zagami, Nakhla and Chassigny

Valérie Malavergne, François Guyot, Karim Benzerara, Isabelle Martinez

▶ To cite this version:

Valérie Malavergne, François Guyot, Karim Benzerara, Isabelle Martinez. Description of new shock-induced phases in the meteorites of Shergotty, Zagami, Nakhla and Chassigny. Journal of Maps, 2001, pp.1297-1305. hal-01158610

HAL Id: hal-01158610
https://hal.science/hal-01158610

Submitted on 1 Jun 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

MAPS, 36, 1297-1305 (2001)

Description of new shock-induced phases in the meteorites of Shergotty, Zagami, Nakhla and Chassigny.

Valérie MALAVERGNE, François GUYOT[(1)], Karim BENZERARA[(1)] and Isabelle MARTINEZ[(2)]

Université de Marne-La-Vallée. Laboratoire des Geomateriaux. Cité Descartes. 5 boulevard Descartes. Champs-sur-Marne. 77454 Marne-La-Vallée. France

[(1)]Laboratoire de Mineralogie-Cristallographie and IPGP. Tour 16. Case 115. 4, place Jussieu. 75252 Paris Cedex 05. France

[(2)]Laboratoire de Géochimie des Isotopes Stables . IPGP - Université Paris 7. 2, place Jussieu. Tour 54-64 -75252 Paris Cedex 05. France

Abstract : The SNC meteorites, Shergotty, Zagami, Nakhla and Chassigny, have been studied by analytical transmission electron microscopy. New phases, characteristic of strong shock conditions, have been discovered in Shergotty, Zagami, Nakhla and Chassigny : calcium-rich majorites in Shergottty, wadsleyite with anomalously elevated iron content in Chassigny and impact melts in Shergotty, Zagami and Nakhla. Cristobalites (α and β polymorphs) observed in Shergotty and Zagami may also be related to shock and are interpreted as backtransformation products of post-stishovite silica polymorphs. Strong shocks corresponding to pressure and temperature conditions characteristic of the Earth's transition zone and lower mantle have occurred in those meteorites. Moreover, impact melts indicate high temperature conditions in localized areas. On the other hand, no massive impact melting is observed in those meteorites, consistently with previous descriptions. These observations evidence highly heterogeneous shock conditions at the scale of few micrometers in these meteorites. Strongly heterogeneous conditions such as those suggested by the present study may help to interpret the preservation in martian meteorites of phases practically unaffected by shock being very close to strongly shock-metamorphized minerals.

Introduction

The SNC meteorites (Shergottites-Nakhlites-Chassignites) are supposed to originate from Mars (e.g. McSween, 1994) and are thus the only putative samples from the red planet that can be studied at present time. This explains the abundant literature devoted to their study and the potential importance of new mineral observations in these rocks. The purpose of the present study is to report new phases characteristic of shock effects in these meteorites.

Petrography of SNC meteorites has been studied extensively since the first investigations of Tschermak (1872) and Michel (1912). Several recent studies emphasized the importance of shock metamorphism in these meteorites as illustrated by the discovery of high-pressure phases (El Goresy *et al.*, 2000) and of new shock features (Langenhorst and Poirier, 2000). Stöffler *et al.* (1986) estimated equilibrium shock pressures and post-shock temperatures for the shergottites : 29 GPa and 200°C for Shergotty, 31 GPa and 220°C for Zagami, 43 GPa and 400-800°C for ALHA 77005. They noticed, however, that stress and temperature accumulations could yield local pressures and temperatures of 60-80 GPa and 1600-2000°C. These uncertainties show the importance of better characterizing SNC meteorites with the aim of better constraining their shock histories. In this study, we report new analytical transmission electron microscopy (ATEM) observations in the four SNC meteorites: Shergotty, Zagami, Nakhla and Chassigny. A brief review of shock features observed in previous studies in those four meteorites is given first.

Shergotty and Zagami are two basaltic meteorites composed mostly of augite and pigeonite clinopyroxenes (70% vol) and maskelynite (25% vol) (e.g. Tschermak, 1872 ; Stöffler *et al.*, 1986 ; Laul *et al.*, 1986 ; Müller, 1993 ; Rubin, 1997). According to Stöffler *et al.* (1986) two main shock effects have been observed in shergottites : (1) mechanical deformations which take place essentially in the solid state, (2) localized melting at grain boundaries. Other shock effects found in Shergotty are (Bischoff and Stöffler, 1992) : fracturing in almost all phases ; mosaicism, planar elements and localized melting in clinopyroxenes and quartz. The TEM study of Müller (1993) showed that the clinopyroxene has complex microstructures consisting of «001» exsolution lamellae of augite in a pigeonite matrix or vice versa, twins, shear fractures. Augite is twinned on (001) that is characteristic of shock deformation. Müller (1993) concluded that the deformation features could be explained by a major shock event connected with the impact ejecting the meteorite into space. Langenhorst and Poirier (2000) report a new high pressure 'eclogite facies' mineral assemblage consisting of omphacite, stishovite and $KAlSiO_8$ hollandite in shock veins of Zagami. With these observations, they infer minimum pressure and temperature for the shock: 30 GPa and 2400-2500°C. The discovery of new high-pressure polymorphs of SiO_2 in Shergotty (Sharp *et al.*, 1999 ; El Goresy *et al.*, 2000) indicates that Shergotty was heavily shocked. In these two last studies, the shock pressure P is evaluated between 30 and 70 GPa.

Nakhla is a magmatic cumulate consisting mostly of augite (~79% vol) and ferroan olivine (Fa_{65-68}) (~16% vol) (e.g. Wadhwa and Crozaz, 1995 ; Rubin, 1997 ; Treiman, 1993 ; McSween, 1994 ; McSween and Treiman, 1998 ; Mikouchi et al., 2000). Fewer shock structures have been characterized in Nakhla than in shergottites (Wadhwa and Crozaz, 1995 ; McSween and Treiman, 1998) suggesting smaller shock pressures than in shergottites. The first TEM investigations on Nakhla (Greshake, 1998) indicated that this meteorite was only weakly shocked with an estimated peak pressure of about 20 GPa.

Chassigny is a dunite composed mostly of olivine (Fa_{32}) (e.g. Floran *et al.,* 1978 ; McSween, 1985, Varela *et al*, 2000). A recent TEM study (Langenhorst and Greshake, 1999) has revealed several shock features such as the conversion of feldspar to maskelynite, the clino-/orthoenstatite inversion, strong mosaicism of olivine, activation of numerous planar fractures and dislocations in olivine. The conclusion of this study is that the characteristic shock pressure of Chassigny is of about 35 GPa. Thus, similar shock pressure than those suggested for shergottites are proposed for Chassigny .

2. Experimental procedure

Millimeter-sized chips of Shergotty, Zagami, Nakhla and Chassigny were provided by the Museum National d'Histoire Naturelle de Paris. Four polished thin slides were made out of chips of each meteorite. They were then mounted on 3 mm Cu rings with central single hole of diameter 600 micrometers, and then thinned by an argon-ion beam, with a voltage of 5 kV and currents of 0.5 mA on each cathode, until perforation of the samples. They were finally coated with a thin film of carbon, to prevent sample charge effects. The samples were studied with a JEOL 2000 EX Transmission Electron Microscope operating at 200 kV associated with a Tracor TN 5400 FX X-ray analyzer which provided energy-dispersive X-ray analyses (EDX). Microanalyses were carried out in scanning transmission mode. Analyses presented in this study have been recorded with live times ranging between 50 and 150 seconds with 8000 to 15000 net counts for the major elements. K factors were determined experimentally with standards (olivines and pyroxenes). Taking into account all this procedure and the uncertainties in the $K_{X/Si}$ factors and in the thickness corrections, the error bars on chemical compositions given below are estimated to be 10% relative for the major elements.

3. ATEM study of phases not previously described in SNC meteorites

3.1. Shergotty (1865, India) and Zagami (1962, Nigeria)

The main minerals described in literature in Shergotty and Zagami (Stopler and McSween, 1979 ; McCoy *et al*, 1992 ; McSween and Treiman, 1998 ; McCoy and Lofgren, 1999 ; Lentz and McSween, 2000) include pigeonite and augite grains with homogeneous Mg-rich cores and variably thick Fe-rich rims. Interstitial maskelynite has also been described as well as shock veins in Zagami (e.g. Langenhorst and Poirier, 2000). In our samples, the pyroxenes in Zagami were finer grained than in Shergotty consistently with previous observations (Stolper and McSween, 1979). The sample of Shergotty that we studied consisted of two distinct areas : the center of the sample was crossed by a vein of maskelynite of about 20 µm in length and 4 µm in width; both sides of the sample consisted of pyroxenes containing planar exsolution lamellae. The sample of Zagami also included a shock melt vein, representing about 40% of the sample, in contact with pyroxenes having similar microstructures than in Shergotty.

In Shergotty, within the pyroxene matrix but close to the vein of maskelynite (about 10 μm away) , four grains of a phase could be evidenced, embedded within an Si-Al-rich-amorphous phase (Fig. 1a). They had the same composition as augites commonly encountered in the meteorite, but with different structure. The compositions of the four grains were found identical yielding a structural formula : $(Mg_{1.60}Fe_{1.00}Ca_{0.88}Al_{0.52})Si_4O_{12}$ (Fig.1a). Selected-area electron diffraction patterns (SAED) on these grains (Fig. 1a) showed that they had a cubic garnet structure, consistent with space group $Ia\bar{3}d$, and can thus be considered as calcium-rich majorites. The majorite crystals, containing neither fractures nor subgrain boundaries, have a maximum length of 600 nm. The cubic symmetry of these majorite grains (Fig 1a) is identical to that of majorites previously described in meteorites (e.g. Price *et al* 1979, Madon and Poirier 1983, Langenhorst *et al.*, 1995 ; Chen *et al* 1996 ; Voegelé *et al*, 2000). The Si-Al-rich-amorphous phase in which majorite crystals were embedded differed from maskelynite by its Si/Al ratio of 6 whereas this ratio varies between 1 and 3 in maskelynites (c.f. Table 1). This amorphous phase extended over an area of about 3 μm in characteristic size and was in contact with clinopyroxenes (augite and pigeonite).

Although cristobalite is not really a shock indicator, it is of interest to report that relatively large crystals of β-cristobalite SiO_2 (typical lengths exceed 1000 nm) were observed in Shergotty (Fig. 1b) embedded within the vein of maskelynite (Table 1) with Si/Al ratio of 2.8, and containing 4.5% of Ca, less than 1% of Fe and traces of S.

In Zagami, grains of α-cristobalite were characterized at the rim of the shock vein. They became slowly amorphous under the electron beam and showed planar defects of thickness less than 20 nm on (101) and on (011) planes. These crystals were found in contact with vein-shaped maskelynite of average thickness of 300 nm (c.f. Table 1 and Fig. 2a). At another rim of the shock vein, large crystals (sizes of about 500 and 1000 nm) of hydroxylapatite (Fig. 2b) were also observed in contact with an Si-rich amorphous phase which had a composition slightly different from that of a maskelynite

(Si/Al = 3.3, c.f.Table 1). Indeed, maskelynites observed in Zagami are close to but often do not match feldspar chemical compositions.

3.2. Nakhla (1911, Egypt)

The Nakhla meteorite represents the Nakhlite group (Nakhla, Lafayette and Governador Valadares). It is a clinopyroxenitic rock principally composed of cumulus augite and olivine grains set in a microcrystalline plagioclase-rich mesostasis. Augite thus comprised about 90% of the TEM sample studied here. Augites were found chemically zoned from core toward slightly Fe-richer rims as described in previous studies (Harvey and McSween, 1992 ; Mikouchi *et al.*, 2000). The studied TEM sample of Nakhla included the contact between pyroxenes and a small amorphous-looking zone in optical microscopy having a length of about 500 μm and a maximum width of 150 μm. In transmission electron microscopy, the amorphous nature of this area is confirmed (Fig. 3a). The chemical composition is $(Mg_{0.48}Fe_{0.25}Ca_{0.29})SiO_3$ close to that of an augite, but traces of S unambiguously distinguish it chemically from adjacent crystalline augite (Fig. 3b) . Its vein-shaped textural setting is smooth, dense with no shock-induced fractures, and no visible subgrain boundaries This amorphous phase is surrounded by augite $(Mg_{0.47}Fe_{0.27}Ca_{0.26})SiO_3$ containing no detectable traces of S (Fig. 3b).

3.3. Chassigny (France, 1815)

The major phase observed was olivine with a mean composition of $(Mg_{0.65}Fe_{0.35})_2SiO_4$ consistently with previous studies (e.g. Floran *et al.,* 1978 ; McSween, 1985, Varela *et al*, 2000). Numerous grains of olivine contain high densities of dislocations. We also observed planar fractures as described in Langenhorst and Greshake, 1999. Most fractures were observed on (100), (010) and (201) planes in olivine. Some grains were also observed practically free of dislocations and planar fractures, suggesting recrystallization.

In contact with olivine, several grains, between 250 and 500 nm in size, of $(Mg_{0.65}Fe_{0.35})_2SiO_4$ composition (Fig. 4a), could not be indexed as olivine, but were found to be consistent only with wadsleyite structure with space group Ibmm. Difference between wadsleyite and ringwoodite could be deciphered from the diffraction pattern. Moreover, the grains of this phase contain numerous planar defects on (010) planes (Fig. 4a) as commonly described in wadsleyite, for example by Price *et al.* (1983) in the Peace River meteorite.

In highly localized areas, over typical sizes less than one μm, an amorphous phase was observed (Fig. 4b) in contact with olivine. The compositions of this phase is close to that of olivine , but significant traces of Na, Al and Mn, not detectable in olivine, are evidenced. In some cases, this amorphous phase is vein-shaped (two observations); in other cases, it is in contact with olivine grains without particular shape (three observations including that shown in Fig. 4b).

4.Discussion

4.1 Ca-rich majorites and wadsleyites.

We have characterized calcium-rich majorites in Shergotty (Fig.1a) and wadsleyite in Chassigny (Fig. 4a). These phases correspond to pressure and temperature conditions characteristic of the transition zone of the Earth which have been reached in these meteorites either during peak shock pressure and temperature conditions or during adiabatic release from even more severe shock conditions.

Majorite is a stable phase in the pressure range between 17 and 24 GPa at temperatures between 1600°C and 2600°C and transforms to a perovskite-type structure at higher pressures (Gasparik, 1992 ; Chen *et al.*, 1996). Majorite phases have been reported in several shocked meteorites, although with lower Ca contents. They are generally located in shock melt veins in highly shocked ordinary chondrites (e.g. Price *et al* 1979, Madon and Poirier 1983, Langenhorst *et al.*, 1995 ; Chen *et al.,* 1996). Our observations of calcium-rich majorites in Shergotty indicate a high-pressure origin of these silicates and clearly demonstrate the print of a shock associated to quite high temperatures. The chemical compositions of those majorites match that of the augites observed in the meteorite. This may suggest that these calcium-rich majorites formed from clinopyroxenes by solid-state reactions induced by the presence of a melt since they were found embedded within a silica-rich amorphous phase. In an experimental study about putative martian mantle compositions up to 23.5 GPa, Bertka and Fei (1997) synthesized majorites between 13 GPa and 23.5 GPa up to 1765°C and observed increasing Ca contents in these garnets with increasing P and T. Moreover, in his study of the enstatite-diopside join between 7 and 22 GPa, Gasparik (1990, 1996) reported a phase (CM phase) of similar composition as the Ca-rich majorite observed in the present work, and predicted that this phase should indeed be a garnet phase resulting from immiscibility in the garnet solid solution. In the iron-free system studied by Gasparik (1996), the lowest Ca content in the CM phase corresponds to 75 mol% diopside whereas the garnet phase that we describe has 62 mol% diopside. This difference could be due to the presence of Fe in the phases observed in Shergotty, which could reduce the immiscibility gap in the garnet solid solution. Further experimental investigations at high pressure are needed for testing this hypothesis and making the observation of Ca-rich majoritic garnets useful for constraining shock and post-shock temperatures in Shergotty.

The chemical compositions of the wadsleyites that we observed in Chassigny match that of the olivines observed in this meteorite. This may suggest that the wadsleyites formed from olivines by solid-state reactions. The high pressure polymorphs of olivine have been reported in several shocked meteorites, generally located in shock melt veins in highly shocked ordinary chondrites (Binns *et al.*, 1969 ; Price *et al*, 1979 ; Price *et al.*, 1983 ;.Madon *et al.*, 1983 ; Chen et al., 1996 ; Lingemann and Stöffler, 1998 ; Chen *et al.*, 1998). Wadsleyites with such elevated iron contents as those observed in the present study (structural formula : $(Mg_{0.65}Fe_{0.35})_2SiO_4$) are inconsistent with high-pressure high-temperature phase diagrams in the Mg_2SiO_4-Fe_2SiO_4 system. The phase that we observed is thus metastable, a likely consequence of non-equilibrium shock conditions.

4.2 Maskelynites and other amorphous phases

Maskelynite has been described in SNC meteorites (e.g. Stöffler et al 1986, 1988) and is generally believed to result from solid state amorphization of plagioclase. Recently, El Goresy *et al* (1997) and Chen and El Goresy (2000) suggested that, in some cases, maskelynites could be glasses quenched from high pressure melts and not diaplectic glasses formed by solid-state phase transitions. Our observations of maskelynites in Shergotty and Zagami are consistent with the interpretation of Chen and El Goresy (2000) suggesting that those amorphous phases that we studied by ATEM are melts rather than phases formed by solid-state amorphization. They do not contain cleavages, they are devoided of intragranular cracks and of shock-induced fractures; they are often vein-shaped (e.g. Fig 2 in Zagami) filling shock-induced fractures in neighboring pyroxene and olivine. We also noticed that the observation of tiny crystals (crisobalite, titanomagnetite, sulfides, phosphates) included within the maskelynites is another argument for their origin from melts, rather than from solid-state transformation of feldspars, in agreement with the interpretation of Chen and El Goresy (2000). Evidence for impact melts is reinforced by the existence in Shergotty of a new amorphous phase with Si/Al ratio of 6 in contact with majorites (Fig. 1a). It has similar composition as silica-rich glasses produced in terrestrial impact craters at shock pressures and temperatures exceeding 60 GPa and 1400°C, respectively (Martinez et al, 1993). In Nakhla and Chassigny, amorphous phases were found close to augite and olivine compositions, respectively, but containing minor elements (e.g. Fig. 3 and 4b) which distinguish them chemically from the crystals. So, it suggests that highly localized non equilibrium melting occurred (e.g. Stöffler *et al.*, 1986 ; Bischoff and Stöffler, 1992 ; Chen and El Goresy, 2000), at a scale only detectable by ATEM.

4.3 Cristobalites

We have characterized free silica in Shergotty and Zagami (α-cristobalite and β-cristobalite, respectively), not in Nakhla and Chassigny. It is important to mention that bulk compositional models of Shergotty predict the presence of quartz (Lodders, 1998). On the other hand, normative olivine, and therefore no free SiO_2, are predicted in Chassigny, Nakhla and Zagami (Lodders, 1998). Free silica was described as new high-pressure post-stishovite silica polymorphs with αPbO_2 and ZrO_2 structures in Shergotty (El Goresy *et al.*, 1998, Sharp et al., 1999). The similarities between the textural setting of the cristobalite crystals observed in the present study (Fig. 2a) with the figure 3 of Sharp et al. (1999) strongly suggest that the cristobalites characterized in the present study indeed result from back transformation of metastable α-PbO_2-structured or ZrO_2-structured SiO_2. Back transformation during sample preparation and TEM observations has been described by these authors under the usual ion milling conditions used in our study and may thus have occurred during sample preparation. Use of cooling stages during ion milling and TEM observation were shown necessary by these authors to characterize the new high-pressure phases. The existence of the silica polymorphs described in Sharp *et al.* (1998 and 1999) and El Goresy *et al.* (2000) suggests that Shergotty and Zagami have experienced pressures exceeding 29 GPa according to criteria given in Stöffler *et al.* 1986. The determination of those shock pressure depends on the stability field of the new high-pressure polymorphs of SiO_2, which would deserve further experimental investigations. Alternatively, but unlikely, the cristobalites that we observed may have formed at low pressure and high temperature immediately after the adiabatic pressure release. In that case, post-shock temperatures exceeding 1400 °C would be needed, also implying elevated peak shock pressures

4.4 Implication for heterogeneity of shock conditions in SNC meteorites

Estimated shock pressures for the SNC meteorites studied here have been given in previous studies : Shergotty 29 GPa (Stöffler *et al.* 1986) and about 40 GPa (El Goresy *et al.*, 2000); Zagami 31 GPa (Stöffler *et al.* 1986) and 30 GPa (Langenhorst and Poirier, 2000); Nakhla about 20 GPa (Greshake, 1998); Chassigny about 35 GPa (Langenhorst and Greshake, 1999). If majorite and wadsleyite were formed during peak shock pressure and temperature conditions, our observations would be indicative of slightly lower pressures in Shergotty and Chassigny, typical of the Earth's mantle transition zone between 12 and 27 GPa. We have calculated shock and post shock temperatures in both augite matrix (case of Shergotty) and olivine matrix (case of Chassigny) (see Table 2) related to the pressures needed for the formation of majorite and wadsleyite. These calculations are performed using the data of Stöffler (1982) and Svendsen and Ahrens (1983). Higher temperatures would definitely be needed to form majorite or wadselyite crystals such as shown in figures 1a and 4a. Even higher pressure estimates do not yield high enough temperatures in Hugoniot calculations. This apparent decoupling between pressure and temperature values may come from very localized heat dissipation (Stöffler *et al.*, 1986 ; Bischoff and Stöffler, 1992 ; Chen and El Goresy, 2000) which would cause, in some areas, strong heating at moderate pressures whereas areas nearby, a few μm away, would be compressed without much heating. This could also help to understand the presence of melts on very localized areas in Shergotty, Zagami, Nakhla and Chassigny, whereas no melting is evidenced at the scale of the petrographic thin sections. This study is thus a direct illustration that the mineralogical and mechanical heterogeneities in the meteorites can cause local stress and temperature concentrations through shock wave interactions at grain boundaries and at free surfaces, as pointed out by Bischoff and Stöffler (1992) and by Chen and El Goresy, 2000. For this reason, single shock pressure and temperature values have no useful meaning for the whole meteorites. This remark is important particularly since analytical transmission electron microscopy results are relevant to very small spatial scales of observation (few nanometers). Strongly heterogeneous conditions such as those suggested by the present study may help to interpret the preservation in martian meteorites of phases practically unaffected by shock being very close to strongly shock-metamorphized minerals.

REFERENCES

BERTKA C.M. and FEI Y. (1997) Mineralogy of the Martian interior up to core-mantle boundary pressures, *J. Geophys. Research*, **102**, B3, 5251-5264.

BINNS R.A., DAVIS R.J. and REED S.J.B. (1969) Ringwoodite, natural $(Mg,Fe)_2SiO_4$ spinel in the Tenham meteorite, *Nature*, **221**, 943.

BISCHOFF A. and STÖFFLER D. (1992) Shock metamorphism as a fundamental process in the evolution of planetary bodies : information from meteorites, *Eur. J. Mineral.*, **4**, 707-755.

CHEN M. and El GORESY A. (2000) The nature of maskelynite in shocked meteorites : not diaplectic glass but a glass quenched from shock-induced dense melt at high pressures, *Earth Planet. Sci. Lett*, **179**, 489-502.

CHEN M., XIE X., EL GORESY A., WOPENKA B. and SHARP T.G. (1998) Cooling rates in the shock veins of chondrites ; constraints on the $(Mg,Fe)_2SiO_4$ polymorph transformations, *Earth Science*, **41**, 522-528.

CHEN M., SHARP T.G., El GORESY A., WOPENKA B. and XIE X. (1996) The majorite-pyrope + magnesiowüstite assemblage : constraints on the history of shock veins in chondrites, *Science*, **271**, 1570-1573.

El GORESY A., DUBROVINSKY L., SHARP T.G., SAXENA S.K. and CHEN M. (2000) A monoclinic post-stishovite polymorph of silica in the Shergotty meteorite, *Science*, **288**, 1632-1634.

El GORESY A., SHARP T.G., WOPENKA B. and CHEN M. (1998) A new very-high-pressure silica mineral in the shergottite : implications for shock metamorphism and the Earth's lower mantle (abstract), *L.P.S.C. XXIX*, **29**, 1707.

El GORESY A., WOPENKA B., CHEN M. and KURAT G. (1997), The saga of maskelynite in Shergotty (abstract), *Meteoritics*, **32**, A38.

FLORAN R.J., PRINZ M., HLAVA P.F., KEIL K., NEHRU C. and HINTHORNE J.R. (1978) The chassigny meteorite : a cumulate dunite with hydrous amphibole-bearing melt inclusion, *Geochim. Cosmochim. Acta*, **42**, 1213-1229.

GASPARIK T. (1996) Melting experiments on the enstatite-diopside join at 70-224 kbar, including the melting of diopside, *Contrib. Mineral. Petrol.*, **124**, 139.

GASPARIK T. (1992) Melting experiments on the enstatite-diopside join at 80-152 kbar,, *J. Geophys. Research*, n°. B11, **97**, 15181-15188.

GASPARIK T. (1990) Phase relations in the transition zone, *J. Geophys. Research*, **95**, 15751-15769.

GRESHAKE A. (1998) Transmission electron microscopy charaterization of shock defects in minerals from Nakhla SNC meteorite (abstract) *Meteoritics*, **33**, A63.

HARVEY R. P. and McSWEEN H.Y., Jr (1992) Petrogenesis of the nakhlite meteorites : evidence from cumulate mineral zoning, *Geochim. Cosmochim. Acta*, **56**, 1655-1663.

LANGENHORST F. and POIRIER J.P. (2000) 'Eclogitic' minerals in a shocked basaltic meteorite, *Phys. Earth Planetary Interior*, **176**, 259-265.

LANGENHORST F. and GRESHAKE A. (1999) A transmission electron microscope study of Chassigny : evidence for strong shock metamorphism, *Meteoritics*, **34**, 43-48.

LANGENHORST F., JOREAU P. and DOUKHAN J.C. (1995) Thermal and shock metamorphism of the Tenham chondrite : a TEM examination, *Geochim. Cosmochim. Acta*, **59**, 1835-1845.

LAUL J.C. and SMITH M.R. (1986) Chemical systematics of the Shergotty meteorite and the composition of its parent body (Mars), *Geochim. Cosmochim. Acta*, **50**, 909-926.

LENTZ R. C. F. and McSWEEN H. Y.,Jr (2000) Crystallization of the basaltic shergottites : insights from crystal size distribution (CSD) analysis of pyroxenes, *Meteoritics*, **35**, 909-926.

LINGEMANN C.M. and STÖFFLER D. (1998) New edvidence for the colouration and formation of ringwoodite in severely shocked chondrites (abstract), *L.P.S.C. XXIX*, **29**, 1308

LODDERS K. (1998) A survey of shergottite, nakhlite and chassignite meteorites whole-rock compositions, *Meteoritics*, **33**, A183-A190.

MADON M. and POIRIER J.P. (1983) Transmission electron microscope observation of α, β ans γ $(Mg,Fe)_2SiO_4$ in shocked meteorites : planar defects and polymorphic transitions, *Phys. Earth Planet. Inter.*, **33**, 31-44.

MARTINEZ I., SCHÄRER U. and GUYOT F. (1993) Impact-induced phase transformations at 50-60 GPa in continental crust: an EPMA and ATEM study, *Earth Planet. Sci. Lett.*, **119**, 207-223.

McCOY T.J. and LOFGREN G. (1999) Crystallization of the Zagami shergottite : an experimental study, *Earth Planet. Sci. Lett.*, **173**, 397-411.

McCOY T.J., TAYLOR G.J., LE L., SCHWANDT C. and HASHIMOTO M. (1992) Zagami : product of a two-stage magmatic history, *Geochim. Cosmochim. Acta*, **56**, 3571-3582.

McSWEEN H.Y., Jr and TREIMAN A.H.(1998), Martian samples, Chapter VI in *Planetary Materials* (J.J. Papike ed.), Reviews in Mineralogy, **36**, Mineralogy Society America.

McSWEEN H.Y., Jr (1994) What we have learned about Mars from SNC meteorites, *Meteoritics*, **29**, 757-779.

McSWEEN H.Y., Jr (1985) SNC meteorites clues to martian petrologic evolution ?, *Rev. Geophys.*, **23**, 391-416.

MICHEL J. (1912) Die Feldspate der Meteoriten. *Tschermak's Miner. Petrogr. Mitt.* **31**, 563-658.

MIKOUCHI T., YAMADA I. and MIYAMOTO M. (2000), Symplectic exsolution in olivine from the Nakhla martian meteorite , *Meteoritics*, **35**, 937-942.

MÜLLER W.F., (1993) Thermal and deformation history of the Shergotty meteorite deduced from clinopyroxene microstructure, *Geochim. Cosmochim. Acta*, **57**, 4311-4322 .

PRICE G.D., PUTNIS A., AGRELL S.O. and SMITH D.G. (1983) Wadsleyite, natural β-$(Mg,Fe)_2SiO_4$ from the peace river meteorite, *Canadian Mineralogist.*, **21**, 29-35.

PRICE G.D., PUTNIS A. and AGRELL S.O. (1979) Electron petrography of shock-produced veins in the Tenham chondrite, *Contrib. Mineral. Petrol.*, **71**, 211-218.

RUBIN A.E. (1997) Mineralogy of meteorite groups, *Meteoritics*, **32**, 231-247.

SHARP T.G., El GORESY A., WOPENKA B. and CHEN M. (1999) A post-stishovite SiO_2 polymorph in the Shergotty meteorite: implications for impact events, *Science,* **284**, 1511-1513.

SHARP T.G., El GORESY A., DUBROVINSKY L. and CHEN M. (1998) Microstructures of shocked silicon dioxide in Shergotty : evidence for multiple poststishovite silicon dioxide polymorphs and extreme shock pressures (abstract), *Meteoritics*, **33**,. A144.

STÖFFLER D., BISCHOFF A., BUCHWALD.V. and RUBIN A.E. (1988) Shock effects in meteotites, *Meteorites and the Early Solar System,* eds Kerridge and Matthews, 165-202.

STÖFFLER D., OSTERTAG R., JAMMES C., PFANNSCHMIDT G., SEN GUPTA P.R., SIMON S.B., PAPIKE J.J. and BEAUCHAMP R.H. (1986) shock metamorphism and petrology of the Sergotty achondrite, *Geochim. Cosmochim. Acta*, **50**, 889-903.

STÖFFLER D. (1982) Density of minerals and rocks under shock compression, in : Numerical data and functional relationships in *Science and Technology*, **1**, *Physical Properties of Rocks*, S.V. Berlin, eds., Landolt-Börnstein, Heidelberg.

STOLPER E. and McSWEEN H.Y. Jr. (1979) Petrology and origin of the shergottite meteorites, *Geochim. Cosmochim. Acta*, **43**, 1475-1498.

SVENDSEN B. and AHRENS T. J. (1983) Dynamic compression of diopside and salite to 200 GPa, *Geophys. Res. Lett.*, **10**, 501-504

TSCHERMAK G. (1872) Die Meteoriten von Shergotty und Gopalpur. *Situngsber. Kaiserl. Akad. Wiss. Wien, Math. Naturwiss. Kl.* **65**, 122-146.

TREIMAN A. H. (1993) The parent magma of the Nakhla (SNC) meteorite, inferred from magmatic inclusions, *Geochim. Cosmochim. Acta*, **57**, 4753-4767.

VARELA M.E., KURAT G., BONNIN-MOSBAH M., CLOCCHIATTI R. and MASSARE D. (2000) Glass-bearing inclusions in olivine of the Chassigny achondrite : heterogeneous trapping at sub-igneous temperatures. *Meteoritics*, **35**, 39-52.

VOEGELE V., CORDIER P., LANGENHORST F. and HEINEMANN S. (2000) Dislocations in meteoritic and synthetic majorite garnets, *Eur. J. Mineral.*, **12**, 695-702.

WADHWA M. and CROZAZ G. (1995) Trace and minor elements in minerals of nakhlites and chassigny : clues to their petrogenesis, *Geochim. Cosmochim. Acta*, **59**, 3629-3645.

Table 1 :

Chemical compositions (wt%) of amorphous phases found in Shergotty and Zagami.

	Shergotty *AP in contact with Maj*	***Shergotty*** *Msk with cristobalite*	***Zagami*** *Msk with cristobalite*	***Zagami*** *Msk with hydroxylapatite*
SiO_2	78.7	59.9	55.4	62.6
MgO	0	0.3	0.1	1.0
Na_2O	**0.05(TiO)*	5.4	5.2	**1.6(TiO)*
CaO	0.50	8.5	10.2	7.8
Al_2O_3	13.6	25.4	28.1	19.1
FeO	2.15	0.5	1.0	7.9

AP = Amorphous phases ; Maj = majorite ; Msk = maskelynite. *These numbers correspond to the TiO concentration and the concentration of Na_2O is 0.

Standard deviations (1 σ) are 5% for Si, Ca, Al, Fe and 15% for the other elements (Na, Ti, Mg).

Table 2 :
Calculations of shock and post shock temperatures in both augite matrix (case of Shergotty) and olivine matrix, (case of Chassigny). We used a gruneisen parameter of 1 and a temperature T_0=273K.

(a) For Shergotty

Shock pressure *(GPa)*	***Peak temperature*** *(K)*	***Post shock temperature*** *(K)*
0	273	273
10	316	292
20	390	343
30	488	411
40	603	488
50	736	574
60	884	666
70	1047	762
80	1226	862
90	1419	965
100	1627	1070

(b) for Chassigny

Shock pressure *(GPa)*	***Peak temperature*** *(K)*	***Post shock temperature*** *(K)*
0	273	273
10	293	274
20	327	287
30	385	320
40	473	373
50	586	441
60	722	521
70	882	611
80	1063	710
90	1264	815
100	1484	925

Figures

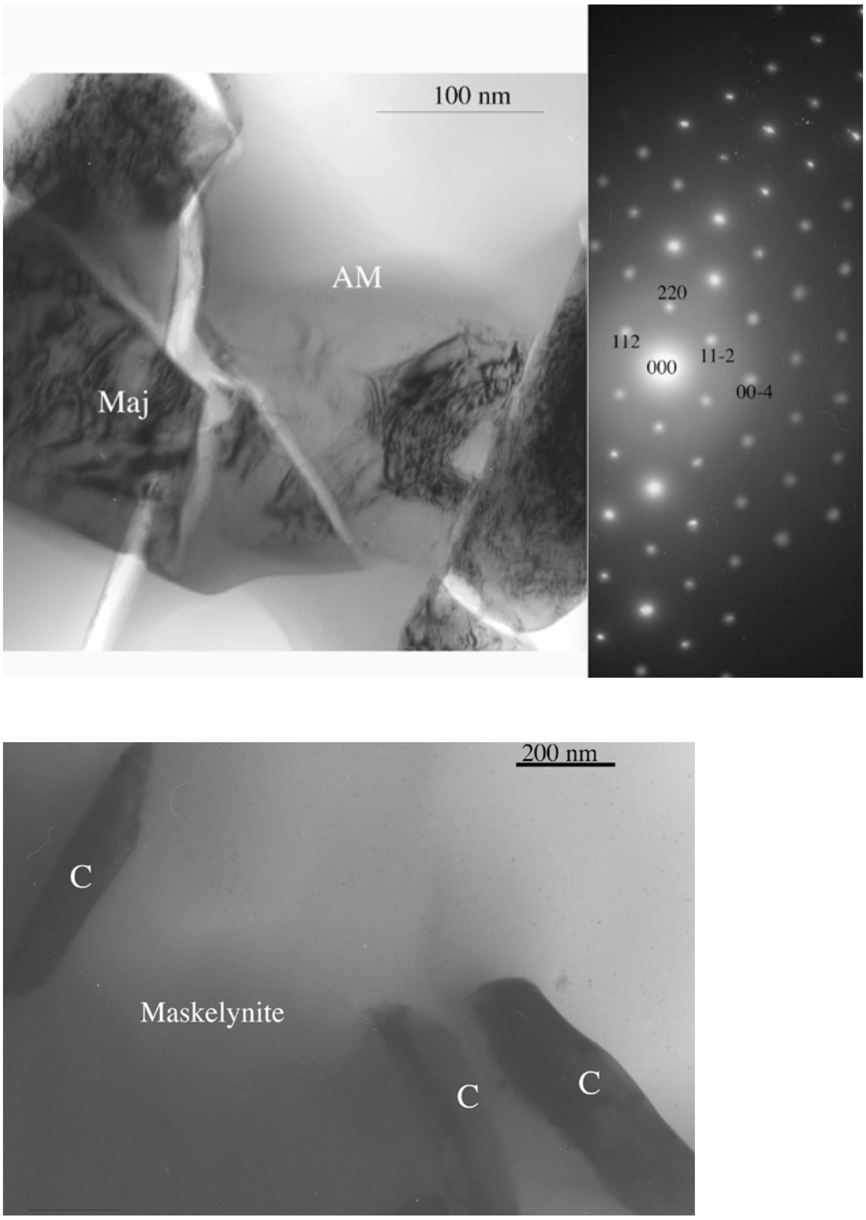


Figure 1 : TEM-micrographs of Shergotty showing **(a)** Si-Al-rich-amorphous phase (AM) in contact with a Ca-rich majorite (Maj) $(Mg_{1.60}Fe_{1.00}Ca_{0.88}Al_{0.52})Si_4O_{12}$ with a lattice parameter of a=11.39(22)Å. The cubic symetry consistent with space group $Ia\bar{3}d$ is evidenced by the absence of (110) reflection in SAED which should occur with the tetragonal symetry.of majorite; **(b)** β-cristobalite (C) in contact with Si-Al-rich amorphous phase (A).

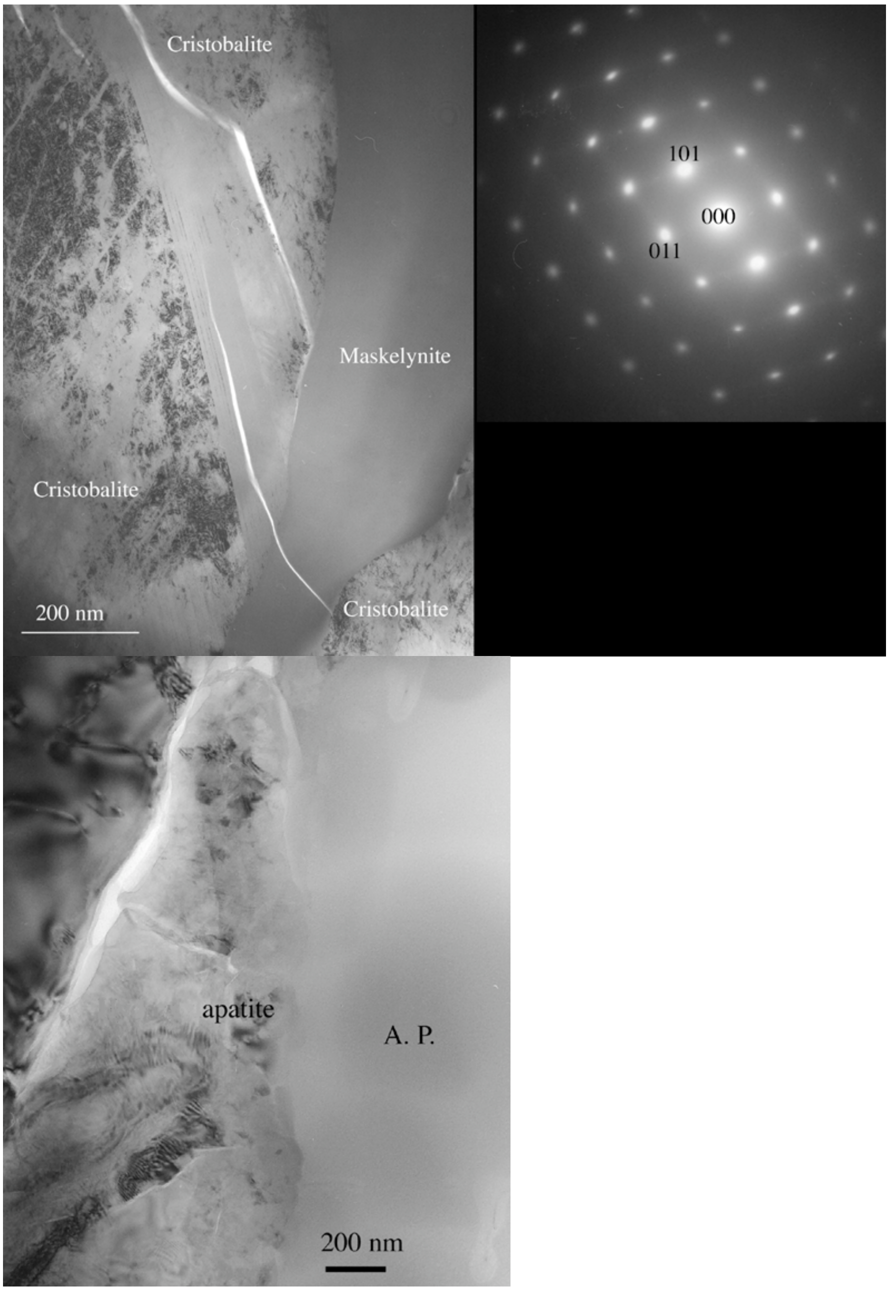


Figure 2 : TEM-micrographs of Zagami showing : **(a)** α-cristobalite in contact with thick veins of maskelynite. **(b)** hydroxylapatite in contact with an Si-rich amorphous phase (AP) which had a composition slightly different from that of a maskelynite (Si/Al = 3.3, c.f.Table 1).

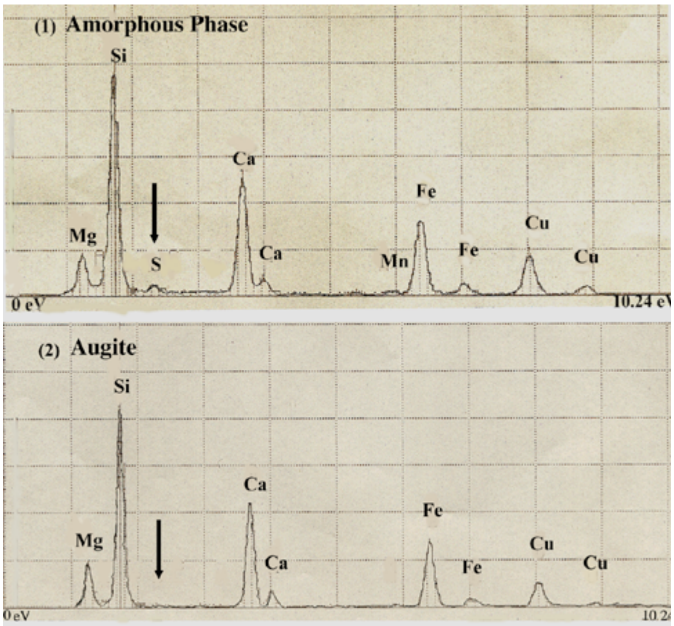
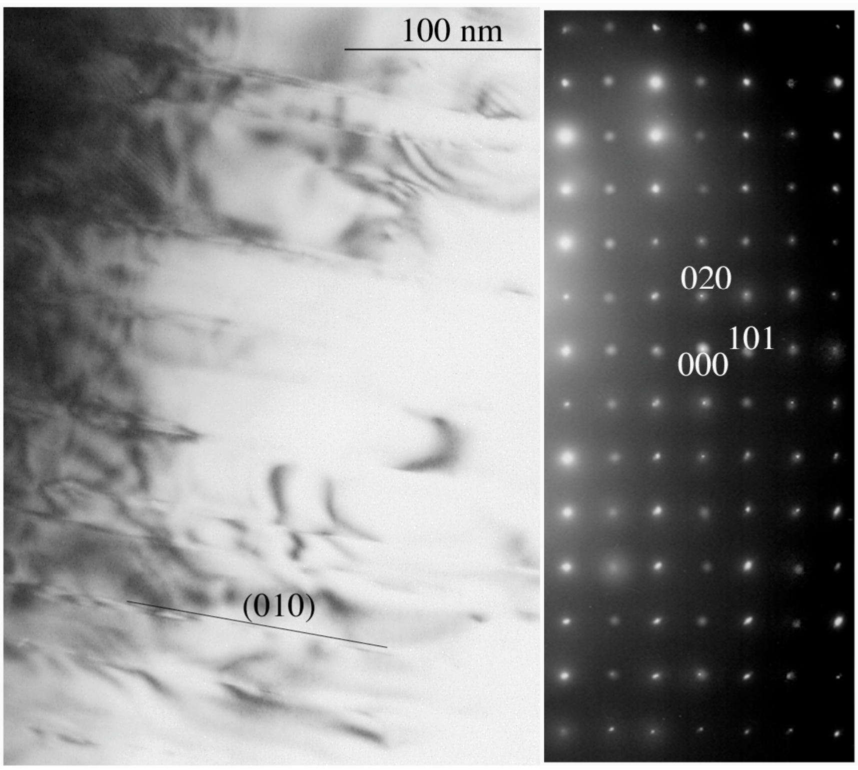


Figure 3 : **(a)** TEM-micrographs of Nakhla showing amorphous phase (AP) and augite **(b)** EDX spectra of (1) amorphous phase ($(Mg_{0.48}Fe_{0.25}Ca_{0.29})SiO_3$) in Nakhla, and (2) augite ($(Mg_{0.47}Fe_{0.27}Ca_{0.26})SiO_3$) in contact with A.P. The net count number is around 600 for highest peak of Si. Traces of S unambigously distinguish it chemically from adjacent crystalline augite.



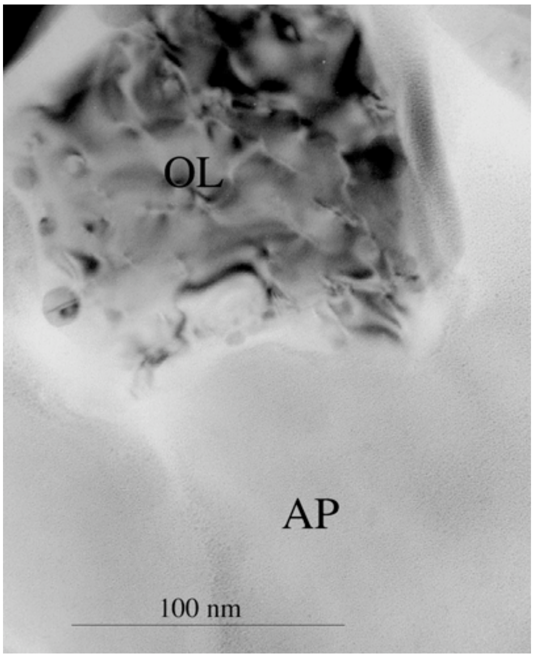


Figure 4 : TEM micrographs of Chassigny showing : **(a)** $(Mg_{0.61}Fe_{0.39})Si_2O_4$ wadsleyite with planar fractures on (010). Lattice parameters : a=8.22(15)Å, b=11.40(20)Å and c=5.67(10)Å. The pattern is consistent with orthorombic symetry (space group Ibmm). The SAED is not compatible with a ringwoodite diffraction pattern, because (020) and (101) reflections should be present in an Fd3m cubic symetry group ringwoodite indexation. The SAED is not compatible with an olivine diffraction pattern ; **(b)** $(Mg_{0.60}Fe_{0.40})Si_2O_4$ amorphous phase (AP) containing minor Na, Al and Mn in contact with crystalline olivine (OL) $(Mg_{0.64}Fe_{0.36})Si_2O_4$.